EFFECT OF UNSTEADINESS AND NOZZLE ASYMMETRY ON THRUST OF A MICRO THRUSTER

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Abstract: Due to the smallness in size and short duration of propulsion pulses for solid-propellant micro-thrusters, unsteady characteristics and/or fabrication errors may cause appreciable effects on the total thrust. In this study flow field in a micro-thruster nozzle was analyzed for unsteady and steady states to estimate the characteristic time (τ) for flow development and decay, and also to see the effect of distortion in nozzle expansion angle on the magnitude and direction of the thrust. Navier-Stokes equation was solved using FLUENT6.3, for 2D-planar and conical nozzle of 200 micron throat diameter. RNG k-ε model was used for turbulence modeling.

Key words: Micro solid-propellant thruster, Micro nozzle, Unsteadiness, Asymmetry, Characteristic time

1. INTRODUCTION

Micro thrusters operating on a variety of propellants provide motion power for main propulsion and attitude or orbit control to micro satellites or micro UAV [1]. A micro thruster using solid propellants is quite commonly used with a number of advantages such as flexibility in propellants, easy size enlargement or reduction, no need for fuel tank/tubing or valves, and no leakage problem. The utmost advantage, however, will be the simple structure, with just four stationary components of simple shapes - propellant, combustion chamber partially filled with propellants, igniter, and the nozzle.

The supersonic nozzle is the key element in every thruster. In a micro thruster, the thruster nozzle is small with the throat diameter of a few hundred microns and the overall length of a few mm. Due to the smallness in size, a small error in geometric dimensions may cause an appreciable effect on the performance. Also the duration of each propulsion pulse is very short with solid-propellant micro-thrusters, less than hundreds of ms, so variation of thrust with time during the initial ignition and final depletion periods needs to be properly estimated in order to predict the total impulse with accuracy.

Those points seem to play an important role in the thrust performance of micro thrusters, but have not been well considered in previous works. In this study the characteristic time (τ) for flow development and decay was numerically analyzed by solving the unsteady flow field in a micro thruster nozzle, and compared with a simple theoretical model. Also, in order to see the effect of nozzle asymmetry on thrust, a nozzle of distorted geometry was analyzed with the nozzle axis rotated to one side by 1~5 degrees with throat position and total nozzle expansion angle of 50 degrees unchanged.

Navier-Stokes equation was solved using FLUENT 6.3, for a 2D-planar and a conical nozzle of 200 micron throat diameter. Volume of the stagnation chamber was 0.393 mm^3, and RNG k-ε model was used for turbulence modeling.

2. NUMERICAL METHODS

Computation domain was taken at least 20 times as large as the nozzle after trying a number of different domain sizes, in order to minimize the potential errors coming from the domain boundaries. The number of grid points ranged 76,500~81,000 depending on the nozzle used, and grids were made more densely populated near the throat and nozzle wall so that the boundary layer and the supersonic velocity development could be accurately simulated. Schematic of the grids near the throat is shown in Fig. 1, and air was used as the working fluid.

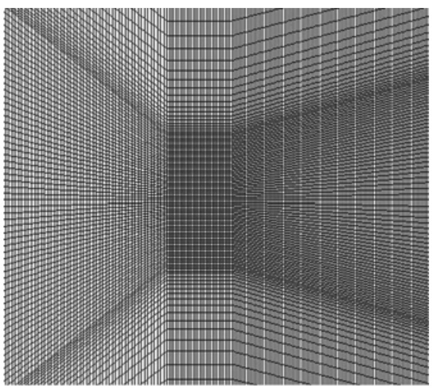


Fig. 1: Schematic of the grids near the nozzle throat.

3. RESULTS AND DISCUSSIONS

3.1 Fundamental Unsteady Characteristics

In order to obtain the unsteady characteristics of pressure and thrust variation during the startup and depletion periods, unsteady flow field through a micro thruster nozzle was analyzed using the step-change mass flux condition at the nozzle inlet. A constant mass flux was suddenly applied at the inlet, and then suddenly dropped to zero after being maintained for a prescribed period of time. Three different mass flow rates were used.

Time variations of chamber pressure and thrust are similar and nearly exponential, both for development and for decay. (Figs. 2 and 3) When the temporal variation of chamber pressure for different mass fluxes is normalized to the pressure in the steady state, the curves for different levels of mass influx coincide very well except for the very initial or final period. (Fig. 4) That is, the unsteady characteristics are not sensitively dependent on the mass flux condition. Time required to attain the steady thrust for the initial ignition period was about 200μs, but that for the final depletion period was a little shorter at about 150μs, irrespective of the mass flux. Chamber pressure and thrust in the steady state are linearly proportional to the mass flux. For most micro thrusters the development time less than 1ms is much shorter than the pulse duration, so total thrust can be estimated through a steady analysis with minor error.

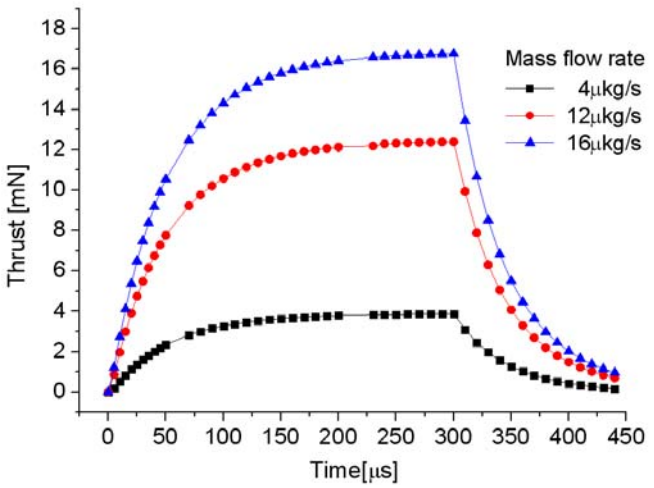


Fig. 2: Change of thrust with time for three different mass input fluxes.

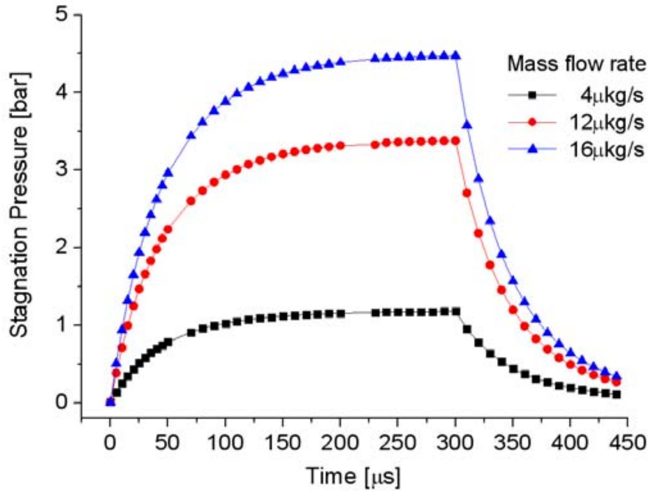


Fig. 3: Change of chamber pressure with time for three different mass input fluxes.

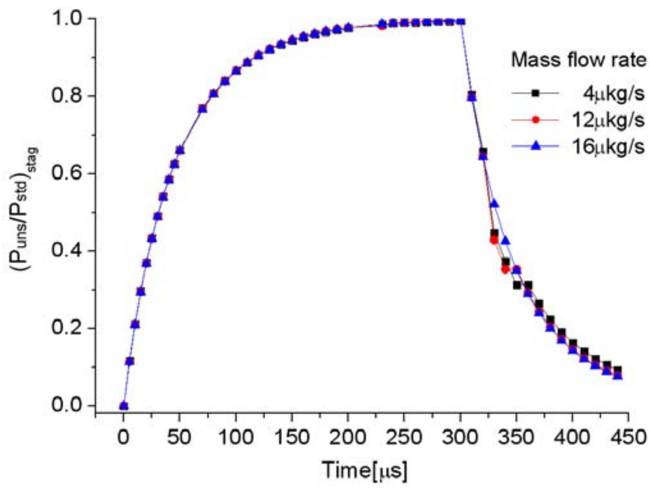


Fig. 4: Change of normalized stagnation pressure with time.

3.2 Effect of Chamber Size on Unsteady Behavior

Since the unsteady behavior comes from the filling or emptying process, both of which are dependent on the chamber size, the same analysis was performed for a nozzle with twice as large a chamber (0.786 mm^3).

Thrust changed nearly exponentially with time, but the speed of approaching the steady state was much lower. (Fig. 5) Temporal variation of chamber pressure was almost the same as that of thrust. When thrust or pressure was normalized to the values at the steady state, it was easily confirmed that the unsteady characteristics were not affected by the mass flux, but strongly affected by the chamber volume. (Fig. 6)

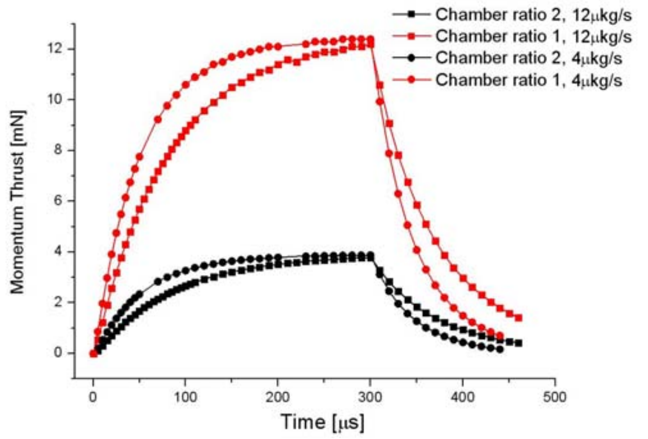


Fig. 5: Change of momentum thrust with time for two different chamber volumes at two different mass fluxes.

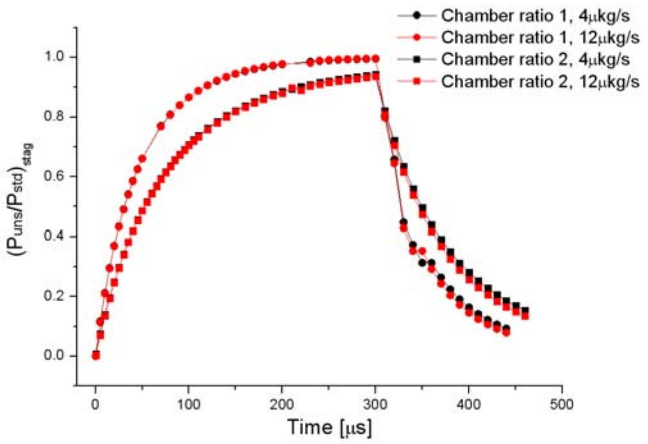


Fig. 6: Change of normalized stagnation pressure with time for different mass fluxes (colors) and chamber volumes (symbols).

3.3 Unsteady Characteristic Time

The change of thrust and pressure during the unsteady state follows the exponential curve quite closely. So the characteristic time (τ) can be easily calculated by fitting the unsteady curves to the exponential function, Eq. (1), and the calculated results are summarized in Table 1.

$$Y = Y_0 + A \cdot \exp(t/\tau) \quad (1)$$

In general, τ was almost the same for thrust and for chamber pressure at about 50μs, irrespective of the mass flux. It was longer for development than for decay (Table 1), by some 25%, which is due to the mass outflow through nozzle while pressure builds up during the initial developing stage. When chamber size was doubled, τ increased by 50-60% (Table 1).

A simple theoretical model for the unsteady behavior, based on a choked condition at the throat, also predicts an exponential change of pressure and thrust, where the characteristic time is linearly proportional to the chamber volume. Calculated τ was close to that estimated by the simple theoretical model, both for development and for decay. (Fig. 7) The simple theory predicts a larger τ than CFD, which can be attributed to the difference in throat area and throat velocity between the true flow field and the nozzle geometry [2]. Deviation from the simple model increases with the period of throat condition deviating from the choked condition, which increases with chamber size. So the change in characteristic time with chamber volume is slower for decay than for development.

Table 1: Summary of Characteristic Times.

Chamber Volume Ratio	1		2	
Mass Flow Rate [μkg/s]	4	12	4	12
	Characteristic Time			
Flow development [μs]	46.3	46.5	73.3	72.4
Flow decay [μs]	36.9	37.4	61.1	59.4

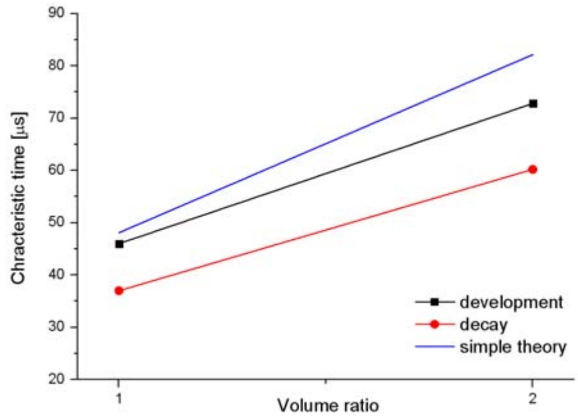


Fig. 7: Comparison of the calculated characteristic time (symbols) and simple theoretical model (line) for two different chamber sizes.

3.4 Effect of Nozzle Angle Asymmetry on Thrust

In order to see the effect of nozzle asymmetry on thrust, top and bottom surfaces of the nozzle was rotated to one side by the same amount of 1~5 degrees with the total nozzle expansion angle of 50 degrees unchanged. (Fig. 8) Thrust in the x-direction did not change appreciably, but agreed quite well with the result of the symmetric case corrected for the angle between the x-axis and the nozzle axis. (Fig. 9) The agreement implies that nozzle distortion does not induce any appreciable change in the flow field inside the nozzle but just changes the flow direction by the same amount as the nozzle-axis rotation. This is confirmed by the profile of x-velocity and density at the exit plane, both of which are seen just shifted or rotated. (Fig. 10) Plume formed downstream of the nozzle exit showed a similar change.

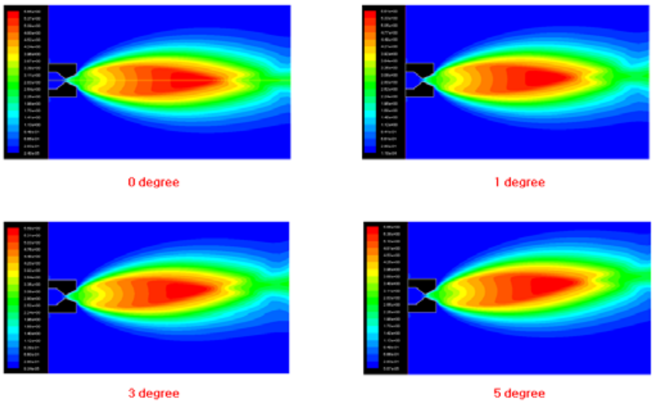


Fig. 8: Mach contours for the distorted nozzle.

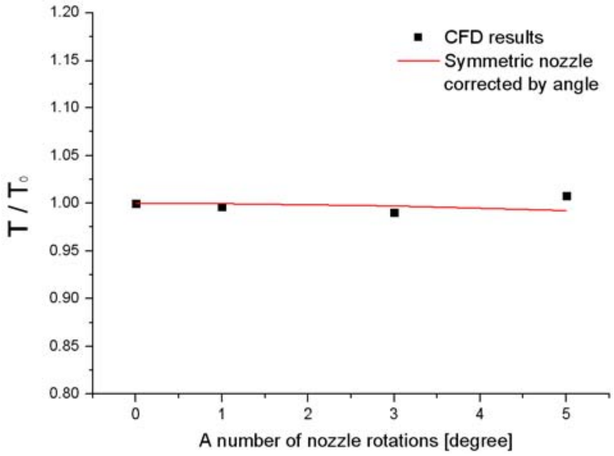
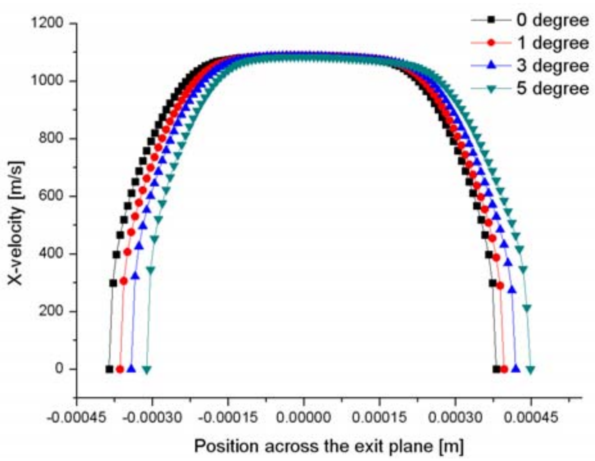


Fig. 9: Thrust in the x-direction for a number of nozzle axis rotations (symbols), normalized to that of the symmetric case and corrected for the angle (line).



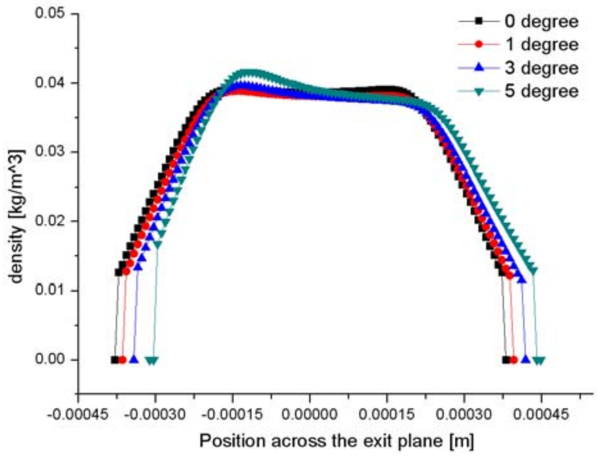


Fig. 10: Profile of x-velocity and density at the exit plane for a number of nozzle axis distortions.

4. Conclusions

(1) Time changes of thrust and chamber pressure are similar and nearly exponential.
(2) Unsteady characteristics were insensitive to the inlet mass flux, but sensitive to the chamber size
(3) Characteristic time was in the order of 0.1 ms, and that for decay was smaller than that for development by about 25%.
(4) When the chamber size was double, τ increased by 50-60%.
(5) Distortion of nozzle angle simply changed the jet axis by the amount of distorted nozzle angle.

ACKNOWLEDGMENTS

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